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Mancini et al.

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(54) **FUEL OXYGEN REDUCTION UNIT**

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F02C 9/44	(2006.01)
F02C 7/22	(2006.01)
F23K 5/08	(2006.01)

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CPC ***F02C 9/28*** (2013.01); ***F02C 7/22*** (2013.01); ***F02C 9/44*** (2013.01); ***F23K 5/08*** (2013.01); *F05D 2220/323* (2013.01); *F05D 2270/303* (2013.01); *F05D 2270/3061* (2013.01); *F23K 2900/05082* (2013.01)

(58) **Field of Classification Search**

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See application file for complete search history.

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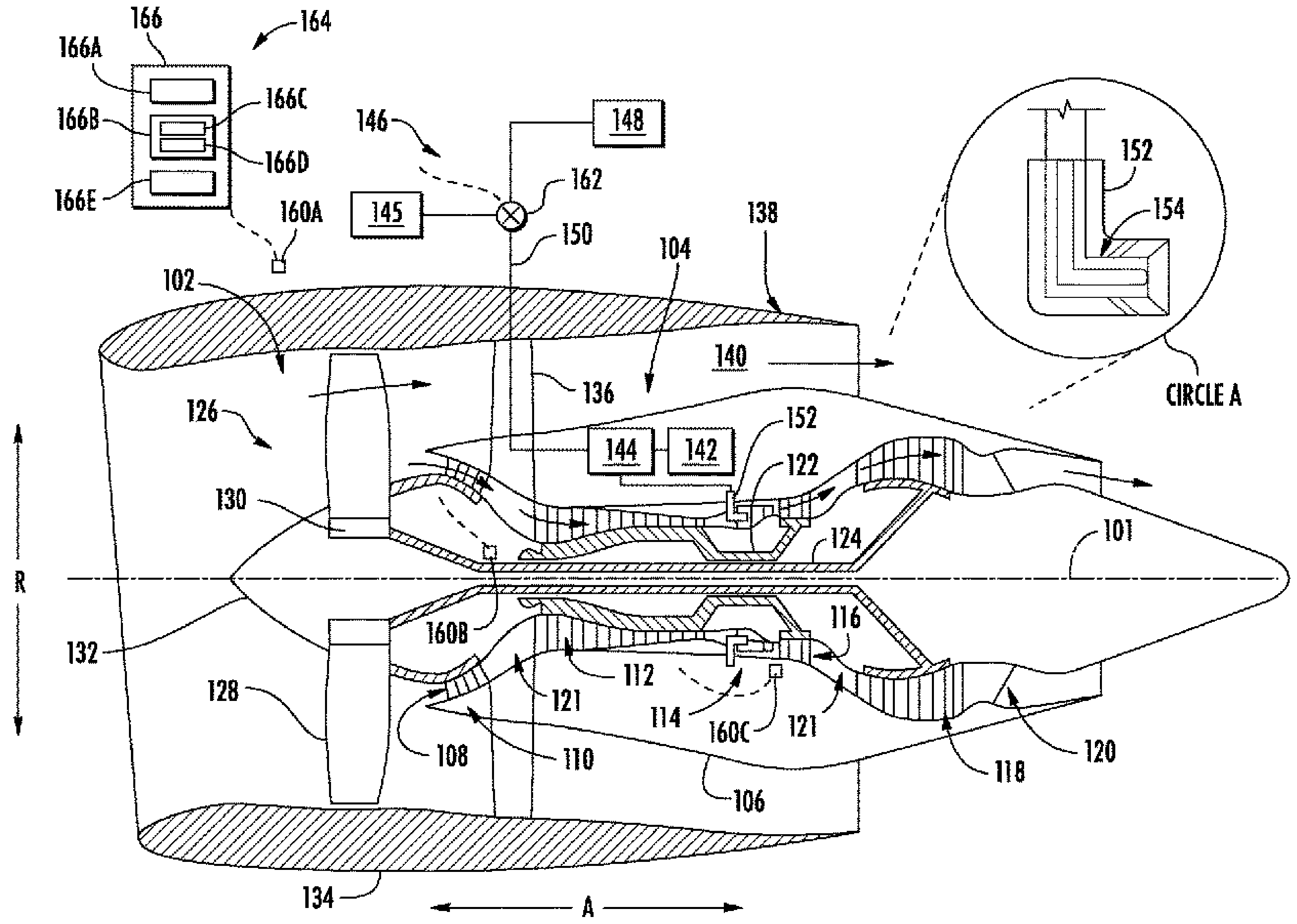
(57) **ABSTRACT**

In one exemplary embodiment of the present disclosure, a method of operating a fuel system for an aeronautical gas turbine engine is provided. The method includes: providing a flow of fuel to a fuel nozzle of the aeronautical gas turbine engine during a wind down condition; operating a fuel oxygen reduction unit to reduce an oxygen content of the flow of fuel provided to the fuel nozzle of the aeronautical gas turbine engine during the wind down condition; and ceasing providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine, the fuel nozzle comprising a volume of fuel after ceasing providing the flow of fuel to the fuel nozzle; wherein operating the fuel oxygen reduction unit comprises operating the fuel oxygen reduction unit to reduce an oxygen content of the volume of fuel in the fuel nozzle to less than 20 parts per million.

20 Claims, 7 Drawing Sheets



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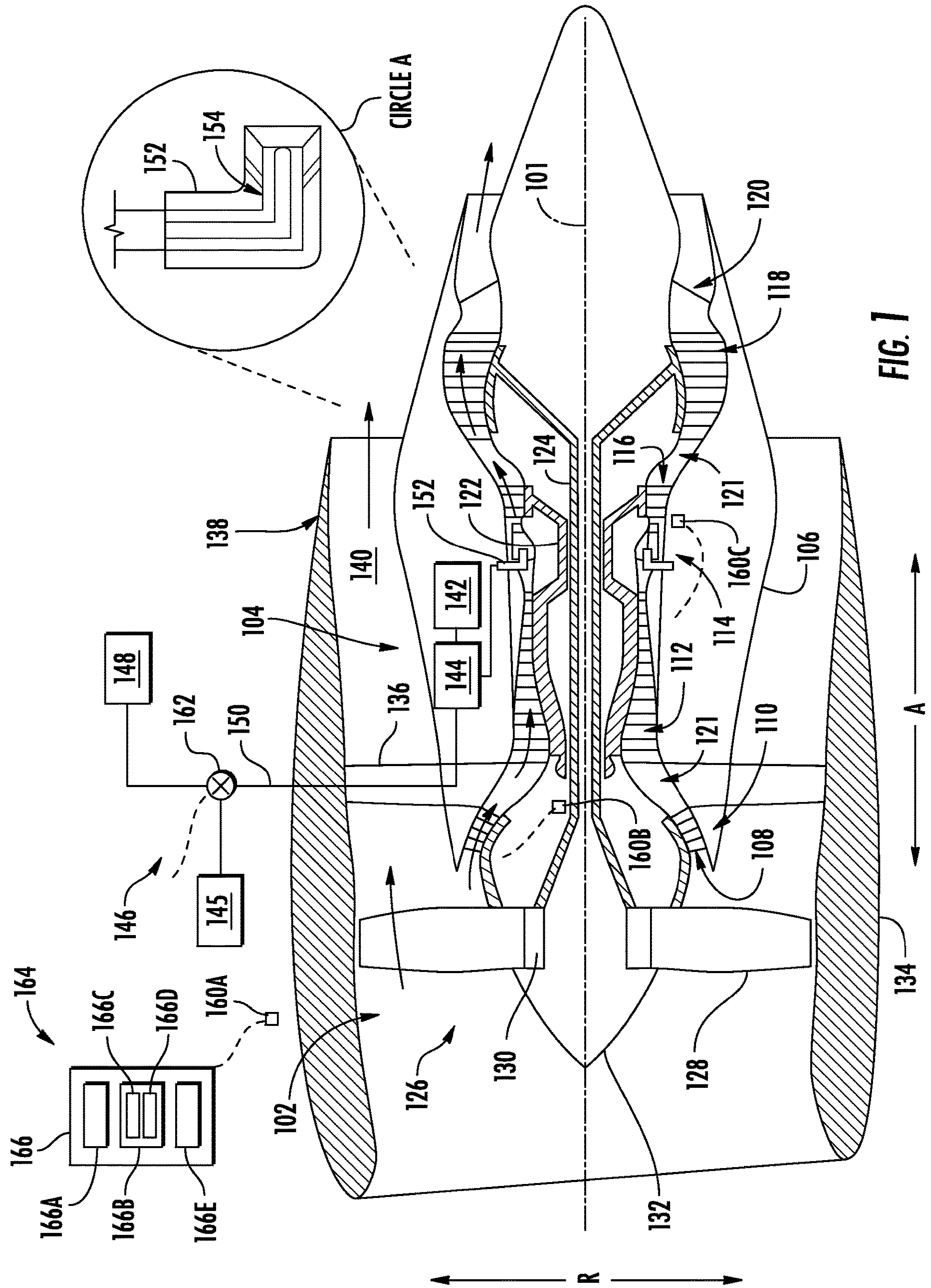
CIRCLE A
152
154
101
120
118
138
140
104
152
122
124
116
121
142
144
114
160C
106
148
162
150
136
112
121
110
160B
108
146
145
164
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166A
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166E
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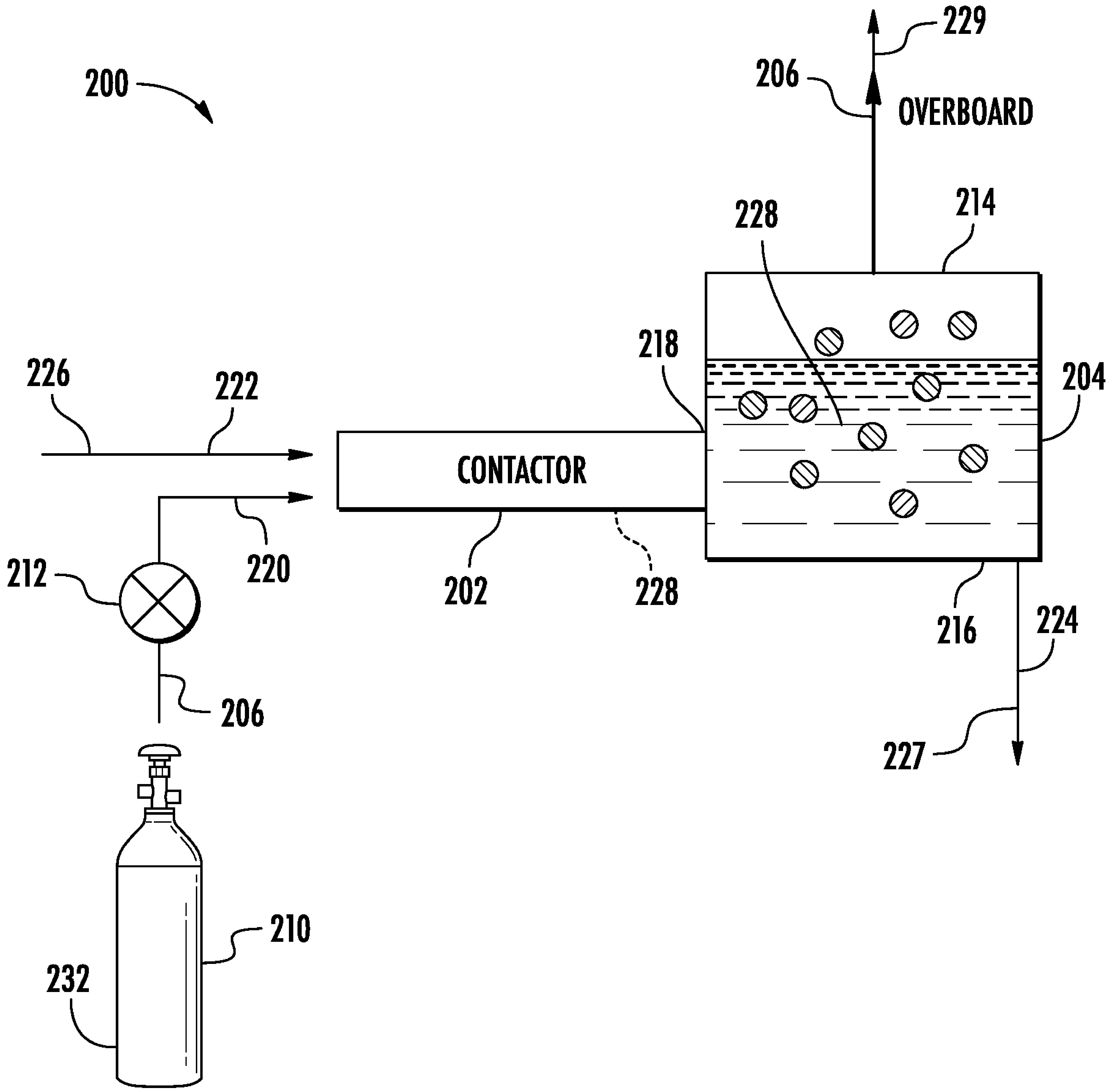
FIG. 1



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OVERBOARD
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CONTACTOR
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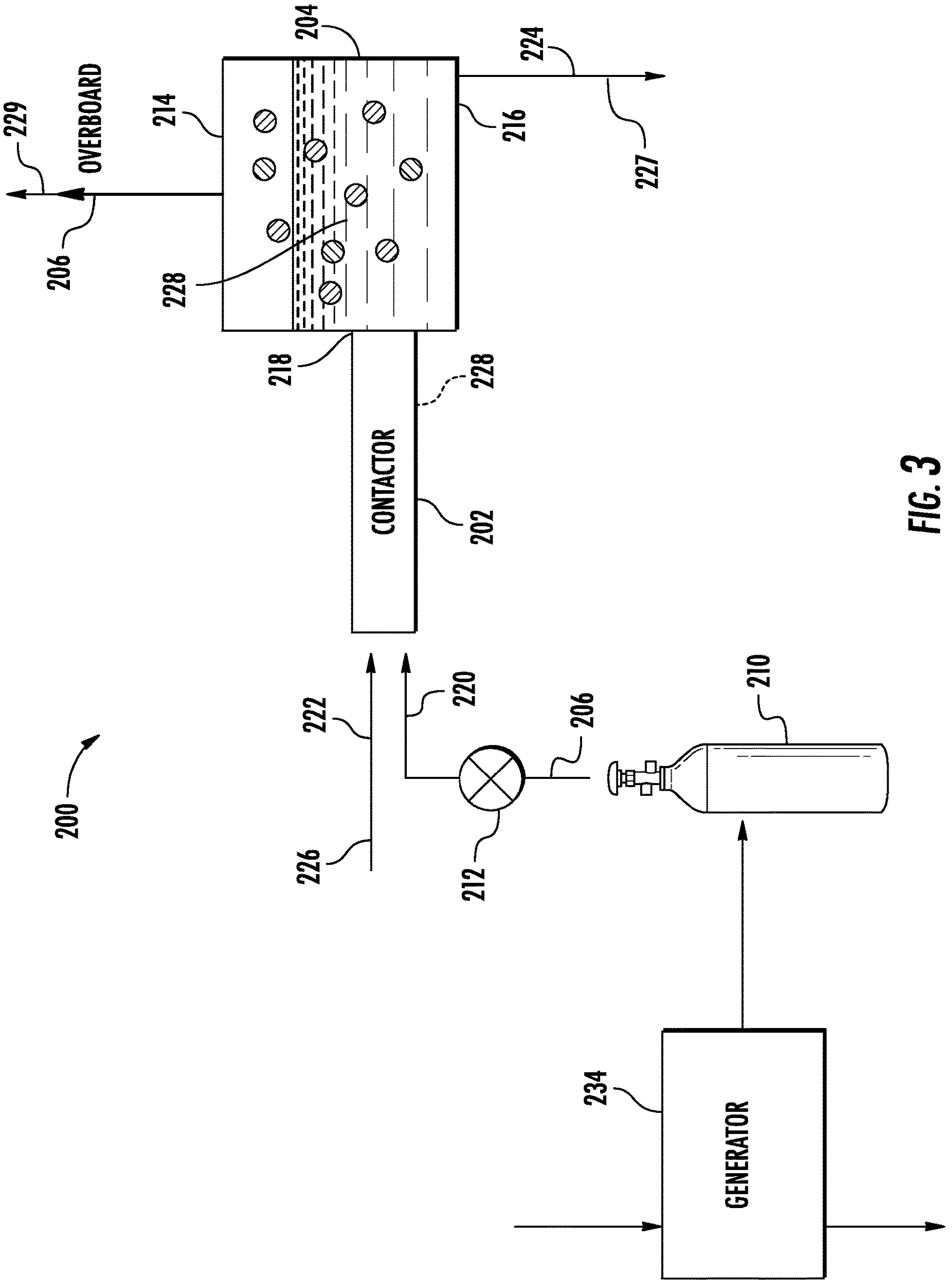
FIG. 2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GENERATOR

FIG. 3

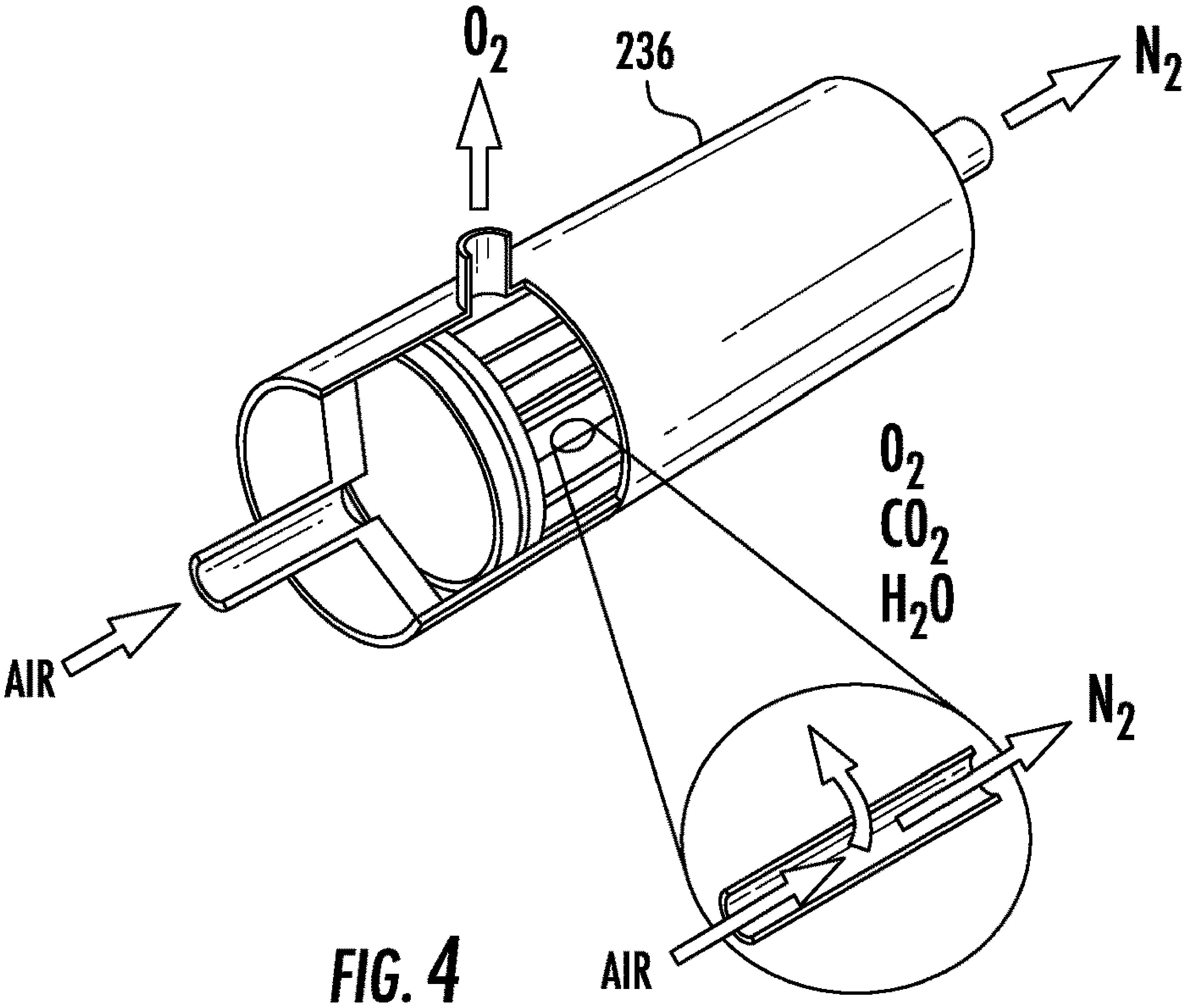


FIG. 4

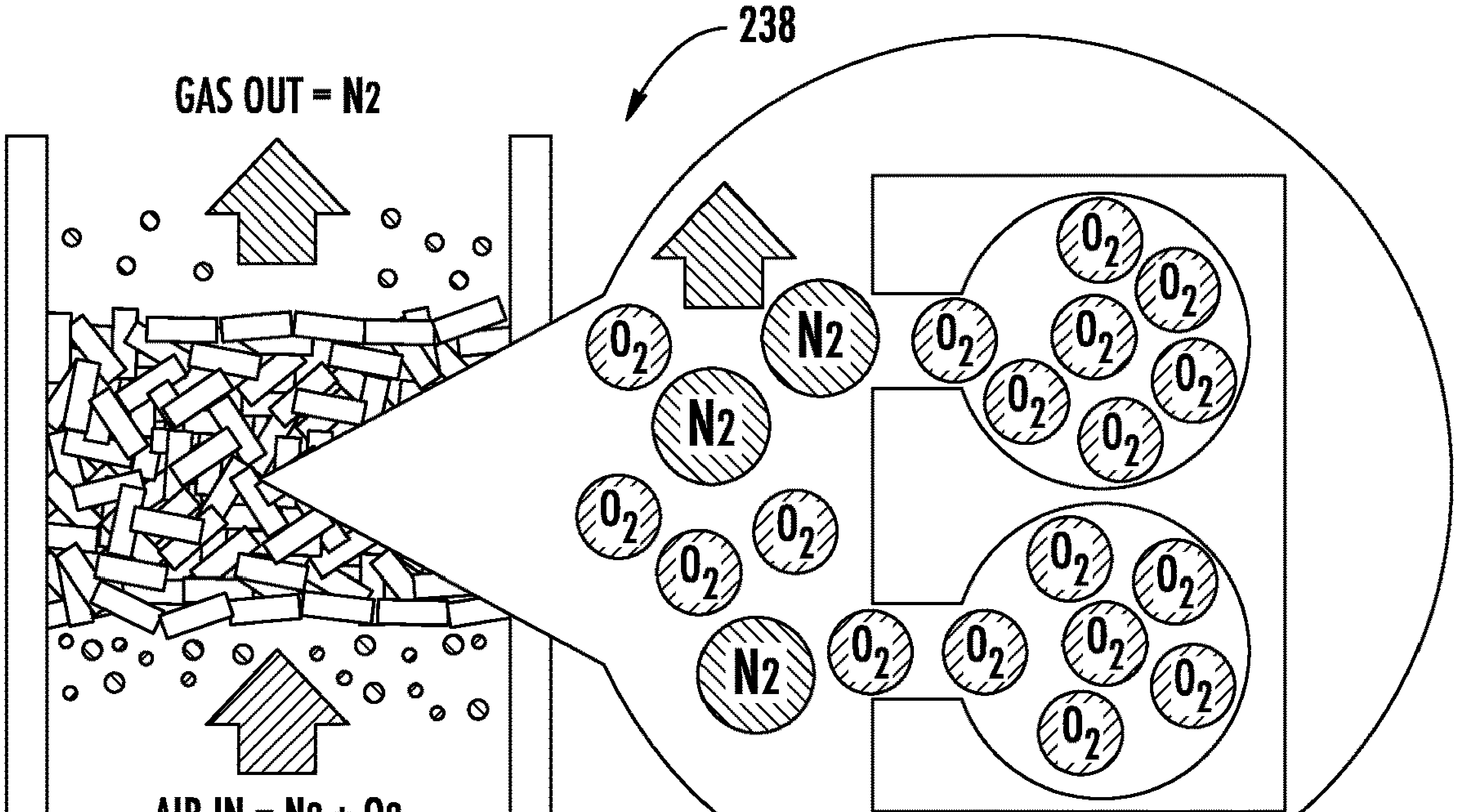
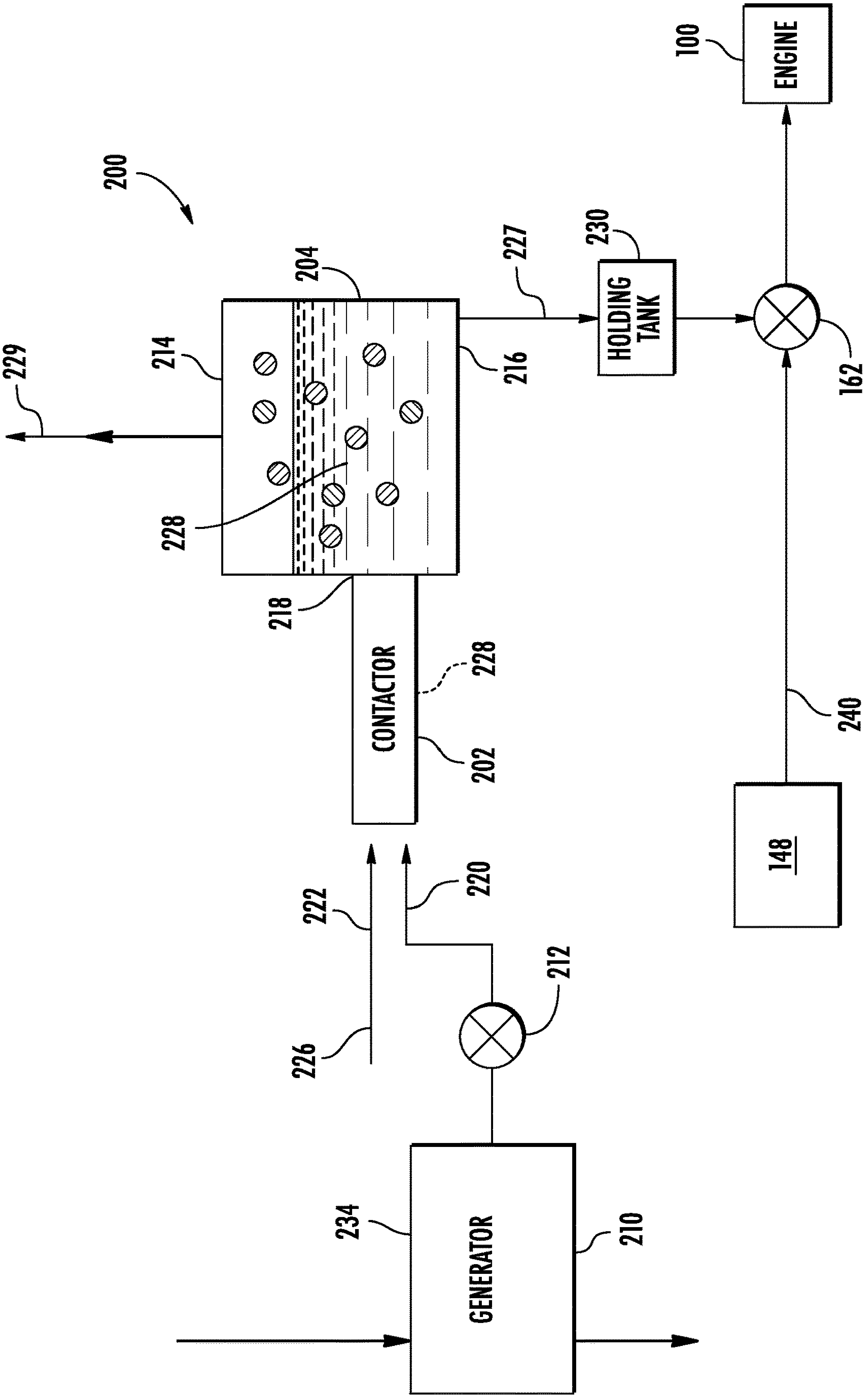


FIG. 5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HOLDING TANK
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162
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CONTACTOR
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226
148
146
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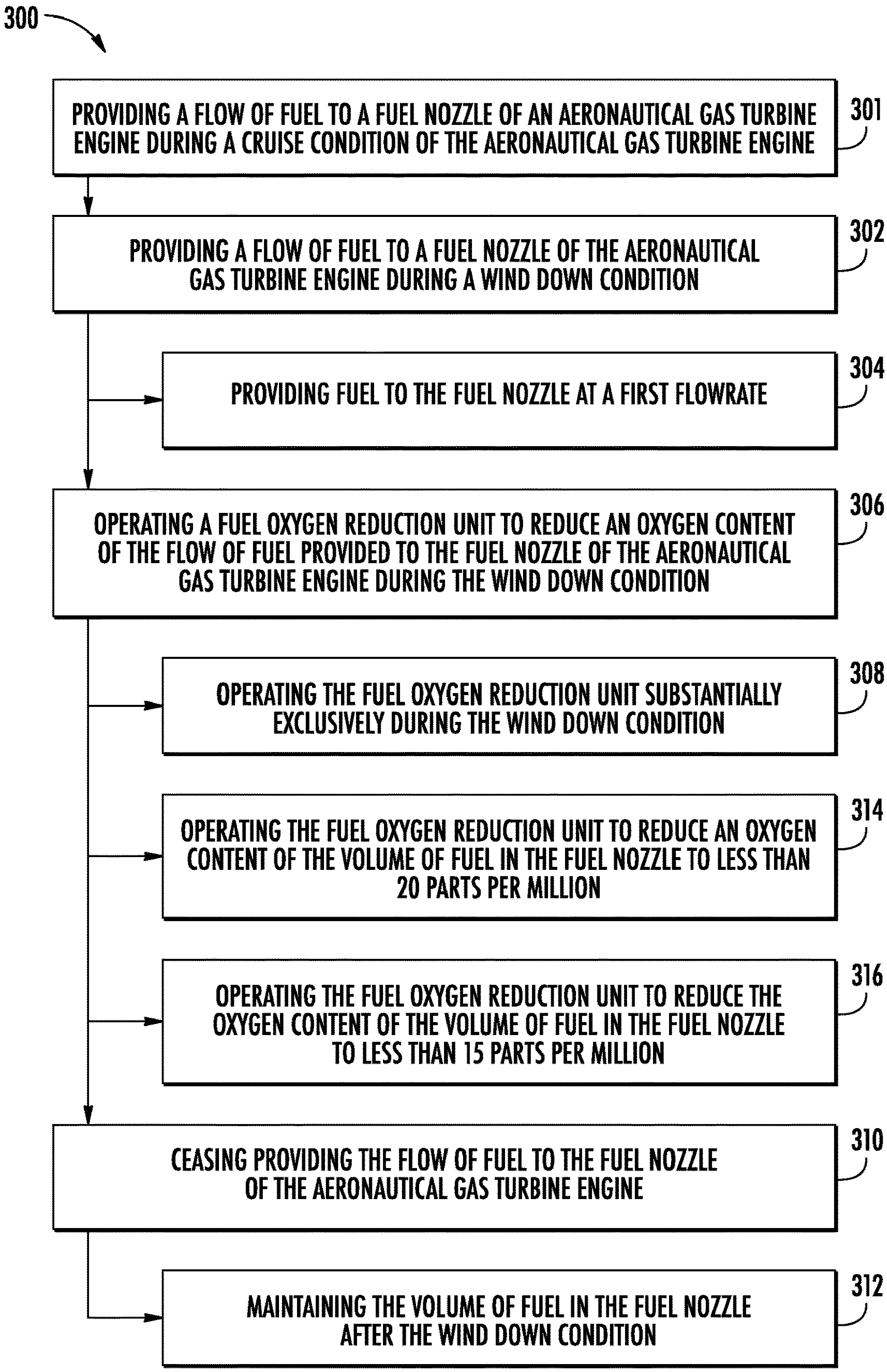
GENERATOR
210

FIG. 6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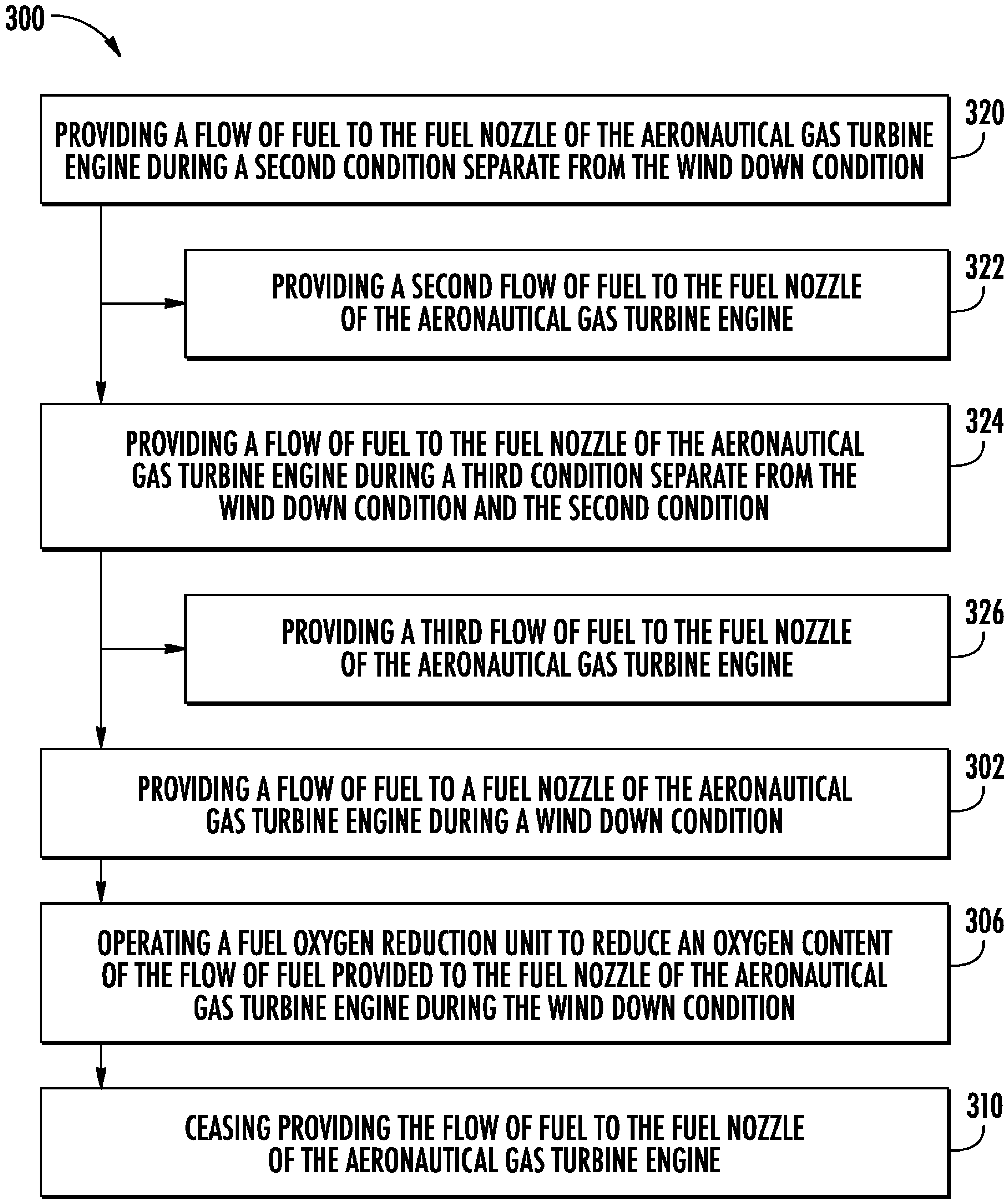
PROVIDING A FLOW OF FUEL TO A FUEL NOZZLE OF AN AERONAUTICAL GAS TURBINE ENGINE DURING A CRUISE CONDITION OF THE AERONAUTICAL GAS TURBINE ENGINE
301
PROVIDING A FLOW OF FUEL TO A FUEL NOZZLE OF THE AERONAUTICAL GAS TURBINE ENGINE DURING A WIND DOWN CONDITION
302
PROVIDING FUEL TO THE FUEL NOZZLE AT A FIRST FLOWRATE
304
OPERATING A FUEL OXYGEN REDUCTION UNIT TO REDUCE AN OXYGEN CONTENT OF THE FLOW OF FUEL PROVIDED TO THE FUEL NOZZLE OF THE AERONAUTICAL GAS TURBINE ENGINE DURING THE WIND DOWN CONDITION
306
OPERATING THE FUEL OXYGEN REDUCTION UNIT SUBSTANTIALLY EXCLUSIVELY DURING THE WIND DOWN CONDITION
308
OPERATING THE FUEL OXYGEN REDUCTION UNIT TO REDUCE AN OXYGEN CONTENT OF THE VOLUME OF FUEL IN THE FUEL NOZZLE TO LESS THAN 20 PARTS PER MILLION
314
OPERATING THE FUEL OXYGEN REDUCTION UNIT TO REDUCE THE OXYGEN CONTENT OF THE VOLUME OF FUEL IN THE FUEL NOZZLE TO LESS THAN 15 PARTS PER MILLION
316
CEASING PROVIDING THE FLOW OF FUEL TO THE FUEL NOZZLE OF THE AERONAUTICAL GAS TURBINE ENGINE
310
MAINTAINING THE VOLUME OF FUEL IN THE FUEL NOZZLE AFTER THE WIND DOWN CONDITION
312

FIG. 7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PROVIDING A FLOW OF FUEL TO THE FUEL NOZZLE OF THE AERONAUTICAL GAS TURBINE ENGINE DURING A SECOND CONDITION SEPARATE FROM THE WIND DOWN CONDITION
320
PROVIDING A SECOND FLOW OF FUEL TO THE FUEL NOZZLE OF THE AERONAUTICAL GAS TURBINE ENGINE
322
PROVIDING A FLOW OF FUEL TO THE FUEL NOZZLE OF THE AERONAUTICAL GAS TURBINE ENGINE DURING A THIRD CONDITION SEPARATE FROM THE WIND DOWN CONDITION AND THE SECOND CONDITION
324
PROVIDING A THIRD FLOW OF FUEL TO THE FUEL NOZZLE OF THE AERONAUTICAL GAS TURBINE ENGINE
326
PROVIDING A FLOW OF FUEL TO A FUEL NOZZLE OF THE AERONAUTICAL GAS TURBINE ENGINE DURING A WIND DOWN CONDITION
302
OPERATING A FUEL OXYGEN REDUCTION UNIT TO REDUCE AN OXYGEN CONTENT OF THE FLOW OF FUEL PROVIDED TO THE FUEL NOZZLE OF THE AERONAUTICAL GAS TURBINE ENGINE DURING THE WIND DOWN CONDITION
306
CEASING PROVIDING THE FLOW OF FUEL TO THE FUEL NOZZLE OF THE AERONAUTICAL GAS TURBINE ENGINE
310

FIG. 8

FUEL OXYGEN REDUCTION UNIT

FIELD

The present subject matter relates generally to a fuel oxygen reduction unit for a vehicle, and a method of operating the same.

BACKGROUND

Typical aircraft propulsion systems include one or more gas turbine engines. The gas turbine engines generally include a turbomachine, the turbomachine including, in serial flow order, a compressor section, a combustion section, a turbine section, and an exhaust section. In operation, air is provided to an inlet of the compressor section where one or more axial compressors progressively compress the air until it reaches the combustion section. Fuel is mixed with the compressed air and burned within the combustion section to provide combustion gases. The combustion gases are routed from the combustion section to the turbine section. The flow of combustion gasses through the turbine section drives the turbine section and is then routed through the exhaust section, e.g., to atmosphere.

Certain operations and systems of the gas turbine engines and aircraft may generate a relatively large amount of heat. Fuel has been determined to be an efficient heat sink to receive at least some of such heat during operations due at least in part to its heat capacity and an increased efficiency in combustion operations that may result from combusting higher temperature fuel.

However, heating the fuel up without properly conditioning the fuel may cause the fuel to "coke," or form solid particles that may clog up certain components of the fuel system, such as the fuel nozzles. Reducing an amount of oxygen in the fuel may effectively reduce the likelihood that the fuel will coke beyond an unacceptable amount.

BRIEF DESCRIPTION

Aspects and advantages of the invention will be set forth in part in the following description, or may be obvious from the description, or may be learned through practice of the invention.

In one exemplary embodiment of the present disclosure, a method of operating a fuel system for an aeronautical gas turbine engine is provided. The method includes: providing a flow of fuel to a fuel nozzle of the aeronautical gas turbine engine during a wind down condition; operating a fuel oxygen reduction unit to reduce an oxygen content of the flow of fuel provided to the fuel nozzle of the aeronautical gas turbine engine during the wind down condition; and ceasing providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine, the fuel nozzle comprising a volume of fuel after ceasing providing the flow of fuel to the fuel nozzle; wherein operating the fuel oxygen reduction unit comprises operating the fuel oxygen reduction unit to reduce an oxygen content of the volume of fuel in the fuel nozzle to less than 20 parts per million.

These and other features, aspects and advantages of the present invention will become better understood with reference to the following description and appended claims. The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

A full and enabling disclosure of the present invention, including the best mode thereof, directed to one of ordinary skill in the art, is set forth in the specification, which makes reference to the appended figures, in which:

FIG. **1** is a schematic, cross-sectional view of a gas turbine engine in accordance with an exemplary embodiment of the present disclosure.

FIG. **2** is a schematic view of a fuel oxygen reduction unit in accordance with an exemplary embodiment of the present disclosure.

FIG. **3** is a schematic view of a fuel oxygen reduction unit in accordance with another exemplary embodiment of the present disclosure.

FIG. **4** is a schematic view of an inert gas generator in accordance with an exemplary embodiment of the present disclosure.

FIG. **5** is a schematic view of an inert gas generator in accordance with another exemplary embodiment of the present disclosure.

FIG. **6** is a schematic view of a fuel oxygen reduction system in accordance with an exemplary embodiment of the present disclosure.

FIG. **7** is a flow diagram of a method of operating a fuel system for an aeronautical gas turbine engine in accordance with an aspect of the present disclosure.

FIG. **8** is a flow diagram of a method of operating a fuel system for an aeronautical gas turbine engine in accordance with another aspect of the present disclosure.

DETAILED DESCRIPTION

Reference will now be made in detail to present embodiments of the invention, one or more examples of which are illustrated in the accompanying drawings. The detailed description uses numerical and letter designations to refer to features in the drawings. Like or similar designations in the drawings and description have been used to refer to like or similar parts of the invention.

For purposes of the description hereinafter, the terms "upper," "lower," "right," "left", "vertical", "horizontal", "top", "bottom", "lateral", "longitudinal", and derivatives thereof shall relate to the invention as it is oriented in the drawing figures. However, it is to be understood that the disclosure may assume various alternative variations, except where expressly specified to the contrary. It is also to be understood that the specific devices illustrated in the attached drawings, and described in the following specification, are simply exemplary embodiments of the invention. Hence, specific dimensions and other physical characteristics related to the embodiments disclosed herein are not to be considered as limiting.

As used herein, the terms "first", "second", and "third" may be used interchangeably to distinguish one component from another and are not intended to signify location or importance of the individual components.

The terms "upstream" and "downstream" refer to the relative direction with respect to fluid flow in a fluid pathway. For example, "upstream" refers to the direction from which the fluid flows, and "downstream" refers to the direction to which the fluid flows.

The terms "coupled," "fixed," "attached to," and the like refer to both direct coupling, fixing, or attaching, as well as indirect coupling, fixing, or attaching through one or more intermediate components or features, unless otherwise specified herein.

The singular forms "a", "an", and "the" include plural references unless the context clearly dictates otherwise.

Approximating language, as used herein throughout the specification and claims, is applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as "about", "approximately", and "substantially", are not to be limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the value, or the precision of the methods or machines for constructing or manufacturing the components and/or systems. For example, the approximating language may refer to being within a 10 percent margin.

Here and throughout the specification and claims, range limitations are combined and interchanged, such ranges are identified and include all the sub-ranges contained therein unless context or language indicates otherwise. For example, all ranges disclosed herein are inclusive of the endpoints, and the endpoints are independently combinable with each other.

As noted above, the inventors of the present disclosure have found that it may be necessary to condition fuel to withstand relatively high temperatures during shutdown conditions of the engine. Aspects of the present disclosure are configured to address such a need by ensuring a volume of fuel remaining in the fuel nozzles of the engine are appropriately conditioned to withstand any additional heat they absorb without coking or otherwise deteriorating beyond a certain threshold.

More specifically, certain exemplary aspects of the disclosure include providing a flow of fuel to a fuel nozzle of the aeronautical gas turbine engine during a wind down condition of the engine and operating a fuel oxygen reduction unit to reduce an oxygen content of the flow of fuel provided to the fuel nozzle of the aeronautical gas turbine engine during the wind down condition. The method may then cease providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine, such that a volume of fuel remains within the fuel nozzle when the engine is shut-down and no longer operating. In these aspects, fuel is not pumped or scavenged out of the fuel nozzle.

With such an exemplary aspect, operating the fuel oxygen reduction unit may include operating the fuel oxygen reduction unit to reduce an oxygen content of the volume of fuel in the fuel nozzle to less than 20 parts per million, such as to less than 15 parts per million. In such a manner, as residual heat stored in the thermal mass heats up components of the engine, including the fuel nozzles, after the engine is shut down, the volume of fuel remaining within the fuel nozzle may be configured to withstand the high temperatures achieved without coking beyond a certain threshold, thus preventing the fuel nozzle from being damaged or worn more quickly than designed.

Notably, as the engine is going through the wind down condition, and, e.g., transitioning from a ground idle condition to a completely shut down condition, the rotating components of the engine create an airflow through the engine, preventing the fuel nozzles form achieving the higher temperatures. Additionally, during these conditions the fuel is still flowing through the fuel nozzles and not just sitting idle. Accordingly, the risk of fuel coking may be higher after the engine is completely shut down than when the engine is operating (even if at lower speeds).

Referring now to the drawings, wherein identical numerals indicate the same elements throughout the figures, FIG. **1** provides a schematic, cross-sectional view of an engine in accordance with an exemplary embodiment of the present disclosure. The engine may be incorporated into a vehicle. For example, the engine may be an aeronautical engine incorporated into an aircraft. Alternatively, however, the engine may be any other suitable type of engine for any other suitable aircraft.

For the embodiment depicted, the engine is configured as a high bypass turbofan engine **100**. As shown in FIG. **1**, the turbofan engine **100** defines an axial direction A (extending parallel to a longitudinal centerline or axis **101** provided for reference), a radial direction R, and a circumferential direction (extending about the axial direction A; not depicted in FIG. **1**). In general, the turbofan **100** includes a fan section **102** and a turbomachine **104** disposed downstream from the fan section **102**.

The exemplary turbomachine **104** depicted generally includes a substantially tubular outer casing **106** that defines an annular inlet **108**. The outer casing **106** encases, in serial flow relationship, a compressor section including a booster or low pressure (LP) compressor **110** and a high pressure (HP) compressor **112**; a combustion section **114**; a turbine section including a high pressure (HP) turbine **116** and a low pressure (LP) turbine **118**; and a jet exhaust nozzle section **120**. The compressor section, combustion section **114**, and turbine section together define at least in part a core air flowpath **121** extending from the annular inlet **108** to the jet nozzle exhaust section **120**. The turbofan engine further includes one or more drive shafts. More specifically, the turbofan engine includes a high pressure (HP) shaft or spool **122** drivingly connecting the HP turbine **116** to the HP compressor **112**, and a low pressure (LP) shaft or spool **124** drivingly connecting the LP turbine **118** to the LP compressor **110**.

For the embodiment depicted, the fan section **102** includes a fan **126** having a plurality of fan blades **128** coupled to a disk **130** in a spaced apart manner. The fan blades **128** and disk **130** are together rotatable about the longitudinal axis **101** by the LP shaft **124**. The disk **130** is covered by rotatable front hub **132** aerodynamically contoured to promote an airflow through the plurality of fan blades **128**. Further, an annular fan casing or outer nacelle **134** is provided, circumferentially surrounding the fan **126** and/or at least a portion of the turbomachine **104**. The nacelle **134** is supported relative to the turbomachine **104** by a plurality of circumferentially-spaced outlet guide vanes **136**. A downstream section **138** of the nacelle **134** extends over an outer portion of the turbomachine **104** so as to define a bypass airflow passage **140** therebetween.

Referring still to FIG. **1**, the turbofan engine **100** additionally includes an accessory gearbox **142**, a primary fuel oxygen reduction unit or system **144**, a secondary fuel oxygen reduction unit **145**, and a fuel delivery system **146**. For the embodiment shown, the accessory gearbox **142** is located within the cowling/outer casing **106** of the turbomachine **104**. Additionally, it will be appreciated that, although not depicted schematically in FIG. **1**, the accessory gearbox **142** may be mechanically coupled to, and rotatable with, one or more shafts or spools of the turbomachine **104**. For example, in at least certain exemplary embodiments, the accessory gearbox **142** may be mechanically coupled to, and rotatable with, the HP shaft **122**. Further, for the embodiment shown, the primary fuel oxygen reduction unit **144** may be coupled to, or otherwise rotatable with, the accessory gearbox **142**. In such a manner, it will be appreciated that the exemplary primary fuel oxygen reduction unit **144** may be driven by the accessory gearbox **142**. In other exemplary embodiments, the exemplary primary fuel oxygen reduction unit **144** may be driven by other sources. Notably, as used herein, the term "fuel oxygen reduction" generally means a device capable of reducing a free oxygen content of the fuel.

Moreover, the fuel delivery system **146** generally includes a fuel source **148**, such as a fuel tank, and a fuel delivery assembly (which may include one or more fuel lines) **150**. The fuel delivery assembly **150** provides a fuel flow through the fuel delivery system **146** to the combustion section **114** of the turbomachine **104** of the turbofan engine **100**. The combustion section **114** includes a plurality of fuel nozzles **152** arranged, for the embodiment shown, circumferentially about the centerline axis **101**. A close-up view of one of the fuel nozzles **152** is shown in the callout Circle A. As shown, the fuel nozzle **152** defines a plurality of fuel flow passages **154**. As will be appreciated, these fuel flow passages **154** define a volume, such that when fuel flow to the nozzle **152** ceases, a volume of fuel remains within the nozzle **152**. The volume of fuel may be at least 10 milliliters of fuel, such as at least 20 milliliters of fuel, such as at least 50 milliliters of fuel, such as at least 100 milliliters of fuel and up to three (3) liters of fuel.

During typical operations, the primary fuel oxygen reduction unit **144** may operate to reduce an oxygen content of a fuel flow to the combustion section **114**, and more particularly to the fuel nozzles **152**. During a wind down condition (defined below), however, it may be necessary to further reduce an oxygen content of the fuel. For example, depending on, e.g., a thermal mass of a core of the engine **100** and a turbine inlet temperature, also referred to as a "T3 temperature," during an idle condition of the engine, heat from the core of the engine **100** may "soak-back" to the fuel nozzles **152**, heating the volume of fuel remaining within the fuel nozzles **152** to a point that the volume of fuel remaining within the fuel nozzles **152** would coke unless an oxygen content of such volume of fuel is reduced below the levels provided by the primary fuel oxygen reduction unit **144**.

Accordingly, as will be explained in more detail below, the secondary fuel oxygen reduction unit **145** may be operated during the wind down condition to ensure that the volume of fuel remaining within the fuel nozzle **152** after the engine has shut down is sufficiently low to prevent the fuel flow coking or otherwise deteriorating past an undesired level when the heat from the core of the engine **100** soaks-back to the fuel nozzle **152**.

Notably, a controller is also provided operable with the turbofan engine **100**, the fuel system **146**, or both to control operations of certain aspects of the turbofan engine **100**, the fuel system **146**, or both to ensure the volume of fuel remaining within the fuel nozzle **152** has an oxygen content below a desired level after the fuel flow to the fuel nozzle **152** has ceased. The aircraft, the turbofan engine **100**, the fuel system **146**, or combinations thereof may include a variety of sensors **160** to sense information indicative of various operating conditions of the turbofan engine **100**, the fuel system **146**, or both, which the controller may base control decisions off of. For example, the exemplary aircraft system shown in FIG. **1** generally includes a aircraft sensor **160**A, an engine rotational speed sensor **160**B, and an engine temperature sensor **160**C. The aircraft sensor **160**A may sense data indicative of, e.g., a weight on any wheels of the aircraft (indicating that the aircraft is on the ground), an altitude of the aircraft, an operating condition of the aircraft (e.g., takeoff mode, cruise mode, taxi mode, shutdown mode, etc.), etc. The engine rotational speed sensor **160**B may sense data indicative of a rotational speed of a shaft of the engine (such as shafts **122**, **124**), the fan **126**, etc. The engine temperature sensor **160**C may sense data indicative of a temperature of the engine, such as the turbine inlet temperature (as shown), compressor exit temperature, etc.

Further, it will be appreciated that the fuel system **146** further includes a control valve **162** operable with the fuel delivery assembly **150**, to selectively provide a fluid flow connection between the secondary fuel oxygen reduction unit **145** and the fuel nozzles **152**. The controller is operably coupled to the control valve **162** and may control operation of the control valve **162** based on, e.g., data received from the sensors **160**.

In one or more exemplary embodiments, the controller **164** depicted in FIG. **1** may be a stand-alone controller **164**, or alternatively, may be integrated into one or more of a controller for the aircraft with which the fuel delivery system **146** is integrated, a controller for the turbofan engine **100** receiving fuel from the fuel delivery system **146**, etc.

Referring particularly to the operation of the controller **164**, in at least certain embodiments, the controller **164** can include one or more computing device(s) **166**. The computing device(s) **166** can include one or more processor(s) **166**A and one or more memory device(s) **166**B. The one or more processor(s) **166**A can include any suitable processing device, such as a microprocessor, microcontroller, integrated circuit, logic device, and/or other suitable processing device. The one or more memory device(s) **166**B can include one or more computer-readable media, including, but not limited to, non-transitory computer-readable media, RAM, ROM, hard drives, flash drives, and/or other memory devices.

The one or more memory device(s) **166**B can store information accessible by the one or more processor(s) **166**A, including computer-readable instructions **166**C that can be executed by the one or more processor(s) **166**A. The instructions **166**C can be any set of instructions that when executed by the one or more processor(s) **166**A, cause the one or more processor(s) **166**A to perform operations. In some embodiments, the instructions **166**C can be executed by the one or more processor(s) **166**A to cause the one or more processor(s) **166**A to perform operations, such as any of the operations and functions for which the controller **164** and/or the computing device(s) **166** are configured, the operations for operating a fuel delivery system **100** (e.g, method **300**), as described herein, and/or any other operations or functions of the one or more computing device(s) **166**. The instructions **166**C can be software written in any suitable programming language or can be implemented in hardware. Additionally, and/or alternatively, the instructions **166**C can be executed in logically and/or virtually separate threads on processor(s) **166**A. The memory device(s) **166**B can further store data **166**D that can be accessed by the processor(s) **166**A. For example, the data **166**D can include data indicative of engine/aircraft operating conditions, and/or any other data and/or information described herein.

The controller **164** is operably coupled to the one or more sensors **160** through, e.g., the network interface **166**E (see, e.g., dotted lines in FIG. **1**), such that the controller **164** may receive data indicative of various operating parameters and other data sensed by the one or more sensors **160** during operation. Further, for the embodiment shown the controller **164** is operably coupled to, e.g., the control valve **162**. In such a manner, the controller **164** may be configured to actuate the control valve **162** in response to, e.g., the data sensed by the one or more sensors **160**.

The network interface **166**E can include any suitable components for interfacing with one or more network(s), including for example, transmitters, receivers, ports, controllers, antennas, and/or other suitable components.

It will be appreciated, that as used herein, the term "wind down condition" of an engine refers to an operating condition or sequence of operating conditions occurring as the gas turbine engine transitions to being in a completely turned-off condition (i.e., when fuel is no longer provided to the fuel nozzles **152**, and the shafts **124** and **122** are not rotating, or rotating at a low speed, e.g., less than 75 revolutions per minute). The wind down condition may include a ground idling condition of the engine as the engine is taxiing to its gate (e.g., for commercial aircraft) or hanger, and/or a shutdown sequence of the engine in which it transitions from the ground idling condition to the completely turned off condition.

It will further be appreciated that the term "thermal mass of the core" refers to a thermal mass defined by the various rotor blades and stator vanes of the high pressure compressor **112** and the high pressure turbine **116**, as well as the HP spool **122**. A relatively high thermal mass of the core of the turbofan engine **100** may render the fuel nozzles **152** more susceptible to fuel coking as a result of heat soak-back.

Similarly, it will be appreciated that a temperature of the core of the engine during idle conditions during and/or leading up to the wind down condition may affect the susceptibility of the volume of fuel within the fuel nozzle **152** after fuel flow thereto has ceased to fuel coking as a result of heat soak-back. In certain exemplary embodiments, the turbine inlet temperature, T3, which may be indicative of an overall temperature of the core, may be at least 1000 degrees Fahrenheit during idle standard day conditions (e.g., sea level and 70 degrees Fahrenheit ambient), such as at least 1100 degrees Fahrenheit, such as at least 1250 degrees Fahrenheit, such as at least 1400 degrees Fahrenheit, such as at least 1500 degrees Fahrenheit, such as at least 1550 degrees Fahrenheit, and up to 3500 degrees Fahrenheit.

Notably, the secondary fuel oxygen reduction unit **145** is designed to operate substantially exclusively during the wind down condition, and is not configured to reduce an oxygen content of a fuel flow during flight operations. In such manner, it will be appreciated that secondary fuel oxygen reduction unit **145** may define a maximum operating time of, e.g., one hour or less per flight mission, such as 30 minutes or less per flight mission. The maximum operating time refers to a maximum amount of time the secondary fuel oxygen reduction unit **145** may reduce an oxygen content of a flow of fuel at, e.g., engine idle fuel flow levels, within about 50 percent of its maximum efficiency. Similarly, in certain exemplary embodiments, it will be appreciated that the aircraft in which the turbofan engine **100** and fuel system **146** are incorporated may define a maximum fuel capacity (e.g., maximum fuel capacity of the tank **148**), and the secondary fuel oxygen reduction unit **145** may define a maximum volume of fuel throughput per flight mission, with the maximum volume of fuel throughput being less than 10 percent of the maximum fuel capacity of the aircraft, such as less than 5 percent of the maximum fuel capacity of the aircraft. The maximum volume of fuel throughput per flight mission of the secondary fuel oxygen reduction unit **145** may refer to a maximum amount of fuel the secondary fuel oxygen reduction unit **145** may effectively treat at a level within about 50 percent of its maximum efficiency.

In addition, it will be appreciated that secondary fuel oxygen reduction unit **145** may define a maximum fuel flowrate. The maximum fuel flowrate capacity refers to a maximum flowrate of fuel that the secondary fuel oxygen reduction unit **145** may effectively treat (i.e., reduce an oxygen content within about 50 percent of its maximum efficiency). It will be appreciated that the aircraft in which the turbofan engine **100** and fuel system **146** are incorporated may define a cruise condition flowrate equal to a flowrate of fuel to the turbofan engine **100** during a cruise condition. The maximum fuel flowrate capacity of the secondary fuel oxygen reduction unit **145** is less than the cruise condition flowrate. Further, the aircraft in which the turbofan engine **100** and fuel system **146** are incorporated may further define a maximum fuel flowrate to the turbofan engine **100** (e.g., a total fuel flowrate to the turbofan engine **100** when the turbofan engine **100** is operated at a rated speed), and the secondary fuel oxygen reduction unit **145** may define a maximum fuel flowrate capacity equal to about 40 percent or less of the maximum fuel flowrate to the turbofan engine **100**, such as about 30 percent or less, such as 20 percent or less, such as 10 percent or less, such as at least 1 percent. For example, the secondary fuel oxygen reduction unit **145** may be configured to effectively treat up to 15 gallons per minute of fuel, such as up to 13 gallons per minute of fuel, such as up to 11 gallons per minute of fuel, such as at least 0.5 gallons per minute of fuel.

It will accordingly be appreciated from the discussion herein that the various systems may be operated to reduce a risk of the volume of fuel remaining in each fuel nozzle **152** after the fuel flow to the fuel nozzles **152** has ceased from coking or otherwise deteriorating more than a threshold amount. For example, the various systems may operate the secondary fuel oxygen reduction unit **145** to reduce an oxygen content of the volume of fuel in each fuel nozzle **152** to less than 20 parts per million, such as to less than 15 parts per million, such as to less than 13 parts per million, such as to less than 12 parts per million, such as to less than 11 parts per million, such as to less than 10 parts per million, such as to less than 9 parts per million, such as to less than 8 parts per million, such as to less than 7 parts per million, such as to less than 6 parts per million, such as to less than 5 parts per million.

Moreover, it will be appreciated that the exemplary turbofan engine **100** depicted in FIG. **1** is provided by way of example only. In other exemplary embodiments, any other suitable engine may be utilized with aspects of the present disclosure. For example, in other embodiments, the engine may be any other suitable gas turbine engine, such as a turboshaft engine, turboprop engine, turbojet engine, etc. In such a manner, it will further be appreciated that in other embodiments the gas turbine engine may have any other suitable configuration, such as any other suitable number or arrangement of shafts, compressors, turbines, fans, etc. Further, although not depicted herein, in other embodiments the gas turbine engine may be any other suitable type of gas turbine engine, such as an industrial gas turbine engine incorporated into a power generation system, a nautical gas turbine engine, etc. Further, still, in alternative embodiments, aspects of the present disclosure may be incorporated into, or otherwise utilized with, any other type of engine, such as reciprocating engines.

Moreover, it will be appreciated that although for the embodiment depicted, the turbofan engine **100** includes the primary fuel oxygen reduction unit **144** and the secondary fuel oxygen reduction unit **145**, in other embodiments, the turbofan engine **100** and/or aircraft incorporating the turbofan engine **100** may only include one of such primary fuel oxygen reduction unit **144** and secondary fuel oxygen reduction unit **145**. Additionally, or alternatively, in certain embodiments the primary fuel oxygen reduction unit **144** (if included) may not be positioned within the turbomachine

104, i.e., within the casing **106** of the turbomachine **104**, and instead may be positioned at any other suitable location.

Further, in still other exemplary embodiments, the turbofan engine **100** (or other gas turbine engine in accordance with one or more exemplary embodiments of the present disclosure), the "secondary fuel oxygen reduction unit **145**" may be the only fuel oxygen reduction unit for the engine. Further, in such a configuration, or others, the secondary fuel oxygen reduction unit **145** may be configured to operate through multiple flight phases/conditions, including one or more of takeoff, climb, cruise, descent, idle, taxi, etc., in addition to the wind down condition. In such a manner, it will be appreciated that the fuel oxygen reduction unit **145** may be configured to operate substantially continuously throughout operation of the engine. In such a configuration, the limitations discussed herein with respect to the maximum throughput of such secondary fuel oxygen reduction unit **145** may still apply.

Referring now to FIG. **2**, a schematic drawing of a fuel oxygen reduction unit **200** for a gas turbine engine in accordance with an exemplary embodiment of the present disclosure is provided. In at least certain exemplary embodiments, the exemplary fuel oxygen reduction unit **200** depicted may be incorporated into, e.g., the exemplary engine **100** and/or fuel delivery system **146** described above with reference to FIG. **1** (e.g., may be the secondary fuel oxygen reduction unit **145** depicted in FIG. **1** and described above, or the primary fuel oxygen reduction unit **144**). Fuel oxygen reduction unit **200** of the present disclose may be a static system that is configured and sized for operating at a prescribed operating condition. Additionally, fuel oxygen reduction unit **200** of the present disclose can be retrofitted on existing engine systems and/or incorporated into a new engine system.

As will be appreciated from the discussion herein, in an exemplary embodiment, the exemplary fuel oxygen reduction unit **200** of FIG. **2** generally includes a contactor **202**, a separator **204**, a stripping gas source **210**, and a valve **212**. In an exemplary embodiment, the exemplary fuel oxygen reduction unit **200** generally defines a single pass gas flowpath or system **206** from the stripping gas source **210** to the contactor **202** and out the separator **204** as described herein.

In exemplary embodiments, the contactor **202** may be configured in any suitable manner to substantially mix a received gas and liquid flow. For example, the contactor **202** may, in certain embodiments, be a mechanically driven contactor (e.g., having paddles for mixing the received flows), or alternatively may be a passive contactor for mixing the received flows using, at least in part, a pressure and/or flowrate of the received flows. For example, a passive contactor may include one or more turbulators, a venturi mixer, etc.

It will be appreciated that the fuel oxygen reduction unit **200** generally provides for a flow of stripping gas **220** to the contactor **202** for mixing with a fuel flow during operation. It will be appreciated that the term "stripping gas" is used herein as a term of convenience to refer to a gas generally capable of performing the functions described herein. The stripping gas **220** may be an actual stripping gas functioning to strip oxygen from the fuel within the contactor, or alternatively may be a sparging gas bubbled through a liquid fuel to reduce an oxygen content of such fuel. For example, as will be discussed in greater detail below, the stripping gas **220** may be an inert gas, such as Nitrogen or Carbon Dioxide (CO2), a gas mixture made up of at least 50% by mass inert gas, or some other gas or gas mixture having a relatively low oxygen content.

Referring to FIG. **2**, in an exemplary embodiment, the separator **204** generally includes a stripping gas outlet **214**, a fuel outlet **216**, and an inlet **218**. It will also be appreciated that the exemplary fuel oxygen reduction unit **200** depicted is operable with a fuel delivery system, such as a fuel delivery system of the gas turbine engine including the fuel oxygen reduction unit **200** (see, e.g., the fuel delivery system **146** of FIG. **1**). The exemplary fuel delivery system **146** generally includes a plurality of fuel lines, and in particular, an inlet fuel line **222** and an outlet fuel line **224**. The inlet fuel line **222** is fluidly connected to the contactor **202** for providing a flow of liquid fuel or inlet fuel flow **226** to the contactor **202** (e.g., from a fuel source, such as a fuel tank) and the outlet fuel line **224** is fluidly connected to the fuel outlet **216** of the separator **204** for receiving a flow of deoxygenated liquid fuel or outlet fuel flow **227**.

Moreover, during typical operations, a flow of stripping gas **220** flows to the contactor **202**, wherein the stripping gas **220** is mixed with the flow of inlet fuel **226** from the inlet fuel line **222** to generate a fuel gas mixture **228**. The fuel gas mixture **228** generated within the contactor **202** is provided to the inlet **218** of the separator **204**. The stripping gas source **210** is selectively in fluid communication with a stripping gas inlet of the contactor **202** for selectively introducing a stripping gas to the contactor **202**.

For the embodiment depicted, the stripping gas source **210** is in fluid communication with the contactor **202** via the valve **212**, which may be actuatable to supply the stripping gas flow **220** to the contactor **202** at a prescribed operating condition. Referring still to FIG. **2**, the valve **212** is downstream of the stripping gas source **210** and upstream of the contactor **202**. The valve **212** is transitionable between a closed position in which the stripping gas source **210** is not in fluid communication with the contactor **202**, and an open position in which the stripping gas **220** flows to the contactor **220**. As described herein, the valve **212** transitions to the open position at a prescribed operating condition. In this manner, the fuel oxygen reduction unit **200** of the present disclosure may operate only during desired engine parameters, e.g., parameters indicating the engine is at the end of the cycle, such as during an engine wind down condition. This enables the fuel oxygen reduction unit **200** of the present disclosure to be a static, smaller, and lighter unit to deoxygenate the fuel at the end of an engine cycle, for example, to prevent coking of a volume of fuel remaining a fuel nozzle after a flow of fuel to the fuel nozzle has ceased. In other words, the fuel oxygen reduction unit **200** of the present disclosure lowers the oxygen content of the fuel, such that a relatively high amount of heat may be added thereto with a reduced risk of the fuel coking (i.e., chemically reacting to form solid particles which may clog up or otherwise damage components within the fuel flow path). As discussed above, such may occur during after a wind down condition of the engine, referred to as soak-back.

Generally, it will be appreciated that during operation of the fuel oxygen reduction unit **200**, the inlet fuel **226** provided through the inlet fuel line **222** to the contactor **202** may have a relatively high oxygen content. The stripping gas **220** provided to the contactor **202** may have a relatively low oxygen content or other specific chemical structure. Within the contactor **202**, the inlet fuel **226** is mixed with the stripping gas **220**, resulting in the fuel gas mixture **228**. As a result of such mixing a physical exchange may occur whereby at least a portion of the oxygen within the inlet fuel

226 is transferred to the stripping gas **220**, such that the fuel component of the mixture **228** has a relatively low oxygen content (as compared to the inlet fuel **226** provided through inlet fuel line **222**) and the stripping gas component of the mixture **228** has a relatively high oxygen content (as compared to the inlet stripping gas **220** provided to the contactor **202**).

Within the separator **204** the relatively high oxygen content stripping gas **220** is then separated from the relatively low oxygen content fuel **226** back into respective flows of an outlet stripping gas **229** and outlet fuel **227**. The separator **204** is configured to separate the fuel/gas mixture **228** into an outlet stripping gas flow **229** and an outlet fuel flow **227** and provide the outlet stripping gas flow **229** to the stripping gas outlet **214** and the outlet fuel flow **227** to the fuel outlet **216**. In an exemplary embodiment, the outlet stripping gas flow **229** is vented out to atmosphere downstream of the separator **204**.

Further, it will be appreciated that the outlet fuel **227** provided to the fuel outlet **216**, having interacted with the stripping gas **220**, may have a relatively low oxygen content, such that a relatively high amount of heat may be added thereto with a reduced risk of the fuel coking (i.e., chemically reacting to form solid particles which may clog up or otherwise damage components within the fuel flow path).

Referring still to FIG. **2**, in an exemplary embodiment, the stripping gas source **210** is a rechargeable bottle of inert gas **232**. The bottle of inert gas **232** could be positioned somewhere on the engine **100** or aircraft. The bottle **232** stores an amount of inert gas that is oxygen free, e.g., a CO2 or N2 gas. The bottle **232** can be recharged at standard intervals, such as between flight missions of the aircraft, or after a certain number of flight missions of the aircraft.

It will be appreciated, however, that in other embodiments, the stripping gs source may be any other suitable source of stripping gas. For example, referring now to FIG. **3**, in an exemplary embodiment, the stripping gas source **210** may be an inert gas generator **234**. The inert gas generator **234** is a device configured to take air from some source, e.g., air from atmosphere, air from a pump, air from a compressor bleed of an engine, etc. and generate a continuous supply of inert gas. In an exemplary embodiment, the inert gas generator **234** may be used to continuously replenish a supply of inert gas to the bottle of inert gas **232** described above.

The inert gas generator **234** may be configured in any suitable manner. For example, FIGS. **4** and **5** depict two exemplary embodiments of an inert gas generator **234** as may be incorporated into the system of FIG. **3**. For example, referring to FIG. **4**, in a first exemplary embodiment, the inert gas generator **234** includes a membrane **236**. The membrane **236** separates oxygen out from nitrogen, for example. In this manner, an oxygen free stripping gas may be continuously provided to the system. Additionally, or alternatively, referring to FIG. **5**, in a second exemplary embodiment, the inert gas generator **234** may be a pressure swing adsorption (PSA) system **238**. The PSA system **238** is used to separate a first gas species from a mixture of gases under pressure according to the species' molecular characteristics and affinity for an adsorbent material. The PSA system **238** of the present disclosure separates a gas such as nitrogen, for example, from oxygen. In this manner, an oxygen free stripping gas is continuously provided to the system.

It will be appreciated, however, that the exemplary fuel oxygen reduction unit **200** described above is provided by way of example only, and that in other embodiments, the fuel oxygen reduction unit **200** may have any other suitable configuration. For example, referring now to FIG. **6**, a schematic drawing of a fuel oxygen reduction system **200** in accordance with another exemplary embodiment of the present disclosure is provided. In at least certain exemplary embodiments, the exemplary fuel oxygen reduction system **200** depicted may be incorporated into, e.g., the exemplary engine **100** described above with reference to FIG. **1** (e.g., may be the secondary fuel oxygen reduction unit **145**, or may be the primary fuel oxygen reduction unit **144** depicted in FIG. **1** and described above).

The embodiment illustrated in FIG. **6** may be configured in a similar manner as the exemplary embodiment illustrated in FIGS. **2** through **5**. However, for the embodiment depicted, the fuel oxygen reduction unit **200** does not include a separate tank **210** and is configured to provide stripping gas **220** generated from the inert gas generator **234**.

Further, it will be appreciated that for the embodiment shown the outlet fuel **227** provided to the fuel outlet **216**, having interacted with the stripping gas **220**, is provided to and stored in a storage tank **230** and can be provided to the engine at a prescribed operating condition. Such may allow for the fuel oxygen reduction unit **200** to be operated at a relatively low throughput for a longer amount of time to generate a sufficient amount of low-oxygen-content fuel for use in the wind down condition to ensure the volume of fuel remaining in the fuel nozzles **152** after shutdown defines a sufficiently low oxygen content.

Referring to FIG. **6**, in an exemplary embodiment, the fuel oxygen reduction system **200** is operable with a fuel delivery system **146**, which includes a primary tank **148** containing a primary fuel flow **240** and a control valve **162** that is downstream of the storage tank **148** and that is downstream of the storage tank **230**. The primary fuel flow **240** has a higher oxygen content than the deoxygenated fuel **227**. The control valve **162** may be actuated to provide the low-oxygen-content fuel for use in the wind down condition to ensure the volume of fuel remaining in the fuel nozzles **152** defines a sufficiently low oxygen content.

Referring now to FIG. **7**, a flow diagram of a method **300** of operating a fuel system for an aeronautical gas turbine engine is provided. The method **300** may be utilized with one or more of the exemplary fuel systems, gas turbine engines, etc. described above, or alternatively may be utilized with any other suitable fuel system.

The method **300** includes operating the aeronautical gas turbine engine during a cruise condition. More specifically, the method **300** includes at (**301**) providing a flow of fuel to a fuel nozzle of the aeronautical gas turbine engine during a cruise condition of the aeronautical gas turbine engine. The method **300** further includes operating the aeronautical gas turbine engine in a wind down condition. More specifically, the method **300** includes at (**302**) providing a flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during a wind down condition. The wind down condition, as noted above, may be an engine operating condition or sequence of operating conditions occurring as the engine transitions to being in a completely turned-off condition (i.e., when fuel is no longer provided to fuel nozzle(s), and the shaft(s) of the engine are not rotating, or are rotating at a low speed). The wind down condition may include a ground idling condition of the engine as the engine is taxiing to its gate at the end of a flight mission (e.g., for commercial aircraft) or hanger, and/or a shutdown sequence of the engine in which it transitions from the ground idling condition to the completely turned off condition. In such a manner, it will be appreciated that providing the flow of fuel to the fuel nozzle at (**302**) includes at (**304**) providing fuel to the fuel nozzle at a first flowrate to facilitate the engine operating at the desire operating speed (e.g., idle).

The exemplary method **300** further includes at (**306**) operating a fuel oxygen reduction unit to reduce an oxygen content of the flow of fuel provided to the fuel nozzle of the aeronautical gas turbine engine during the wind down condition. The fuel oxygen reduction unit may be configured in a similar manner as one or more of the exemplary secondary fuel oxygen reduction units described above with reference to FIGS. **1** through **6**, or alternatively may be any other suitable fuel oxygen reduction unit.

In such a manner, it will be appreciated that in at least certain exemplary aspects, operating the fuel oxygen reduction unit at (**306**) includes at (**308**) operating the fuel oxygen reduction unit substantially exclusively during the wind down condition. In the context of this step, "substantially exclusively" refers to at least 90% of a total operating time within a particular flight mission of an aircraft incorporating the fuel oxygen reduction unit.

In such a manner, it will be appreciated that the fuel oxygen reduction unit may define a maximum operating time of one hour or less per flight mission, such as 30 minutes or less per flight mission.

Additionally, or alternatively, it will be appreciated that an aircraft incorporating the aeronautical gas turbine engine may define a maximum fuel capacity (e.g., a maximum amount of fuel that may be loaded in the fuel tanks of the aircraft during typical operations). The fuel oxygen reduction unit may define a maximum volume of fuel throughput per flight mission, with the maximum volume of fuel throughput of the fuel oxygen reduction unit being less than 10 percent of the maximum fuel capacity of the aircraft.

Additionally, or alternatively, still, the fuel oxygen reduction unit may define a maximum fuel flowrate capacity. The maximum fuel flowrate capacity of the fuel oxygen reduction unit may refer to a maximum flowrate that the fuel oxygen reduction unit may effectively process (i.e., may process at an oxygen reduction level of at least 50% of its maximum oxygen reduction level). Further, as noted above, the method **300** includes operating the aeronautical gas turbine engine during a cruise condition. Operating the aeronautical gas turbine engine during the cruise condition may include providing a fuel flow to a combustion section of the aeronautical gas turbine engine at a cruise condition flowrate. The maximum fuel flowrate capacity of the fuel oxygen reduction unit is less than the cruise condition flowrate. In such a manner, it will be appreciated that the fuel oxygen reduction unit is not a steady state fuel oxygen reduction unit, and instead is a special purpose fuel oxygen reduction unit.

In such a manner, it will be appreciated that in other exemplary aspects, the fuel oxygen reduction unit is configured to operate substantially continuously. In such a configuration, the fuel oxygen reduction unit may still define the maximum fuel flowrate capacity. The maximum fuel flowrate capacity may still be less than the cruise condition flowrate, and the fuel provided to the gas turbine engine may simply not be effectively conditioned. Notably, however, it will be appreciated that depending on the operating temperatures of the gas turbine engine, the fuel flowrate, the resonance time of the fuel within a combustion section of the gas turbine engine, etc., the fuel may not need to be effectively conditioned by the fuel oxygen reduction unit during, e.g., cruise operations. The fuel oxygen reduction unit may still effectively treat substantially all of the fuel flow to the gas turbine engine during a wind down condition.

Referring still to the exemplary aspect of FIG. **7**, the method **300** further includes at (**310**) ceasing providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine, the fuel nozzle comprising a volume of fuel after ceasing providing the flow of fuel to the fuel nozzle. In such a manner, it will be appreciated that in the exemplary aspect shown, ceasing providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine at (**310**) includes at (**312**) maintaining the volume of fuel in the fuel nozzle after the wind down condition. Notably, the volume of fuel remaining in the fuel nozzle may be at least about 10 milliliters, and ceasing providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine at (**310**) may immediately follow the wind down condition of the engine.

The exemplary method **300** may facilitate preventing a fuel within the fuel nozzles from coking or otherwise deteriorating beyond a threshold amount after the wind down condition of the engine, despite a potentially relatively high temperature that may be reached by the fuel as a result of heat soak-back. For example, in the exemplary aspect depicted, it will be appreciated that operating the fuel oxygen reduction unit at (**306**) includes at (**314**) operating the fuel oxygen reduction unit to reduce an oxygen content of the volume of fuel in the fuel nozzle to less than 20 parts per million, and more specifically includes at (**316**) operating the fuel oxygen reduction unit to reduce the oxygen content of the volume of fuel in the fuel nozzle to less than 15 parts per million.

Notably, the method **300** further includes at (**315**) operating the aeronautical gas turbine engine during an idle condition. The gas turbine engine defines a turbine inlet temperature greater than 1000 degrees Fahrenheit while the aeronautical gas turbine engine is operating during the idle condition at (**315**). Further, it will be appreciated that from the discussions above with respect to FIGS. **1** through **6**, the core of the engine may define a relatively high thermal mass. In such a manner, it will be appreciated that the combination of the relatively high turbine inlet temperatures during idle and the relatively high thermal mass, the soak-back may be relatively significant, such that the reduction in oxygen content of the volume of fuel remaining in the fuel nozzle is necessary to reduce a risk of the fuel coking beyond a certain threshold.

Such may allow the volume of fuel remaining in the fuel nozzles to withstand the relatively high temperatures without coking beyond a threshold level.

It will further be appreciated that in certain exemplary aspects, an oxygen level of a fuel flow to the fuel nozzle may be monitored and/or reduced during other operating conditions of the engine. For example, referring now to FIG. **8**, a flow diagram of a method **300** for operating a fuel system for an aeronautical gas turbine engine in accordance with another exemplary aspect of the present disclosure is provided. The method **300** may be utilized with one or more of the exemplary fuel systems, gas turbine engines, etc. described above, or alternatively may be utilized with any other suitable fuel system.

The method **300** of FIG. **8** is similar to the method **300** of FIG. **7**. For example, the method **300** of FIG. **8** generally includes at (**302**) providing a flow of fuel to a fuel nozzle of the aeronautical gas turbine engine during a wind down condition; at (**306**) operating a fuel oxygen reduction unit to reduce an oxygen content of the flow of fuel provided to the fuel nozzle of the aeronautical gas turbine engine during the wind down condition; and at (**310**) ceasing providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine.

However, for the exemplary aspect of FIG. **8**, an oxygen level of a fuel flow to the fuel nozzle may be further monitored and/or reduced during other operating conditions of the engine.

For example, for the exemplary aspect of FIG. **8**, the method **300** includes at (**320**) providing a flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during a second condition separate from the wind down condition. For the exemplary aspect depicted, an oxygen content of the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during the second condition is greater than the oxygen content of the volume of fuel in the fuel nozzle after ceasing providing the flow of fuel to the fuel nozzle. For example, in certain exemplary aspects, the oxygen content of the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during the flight condition is at least 1.5 times greater than the oxygen content of the volume of fuel in the fuel nozzle after ceasing providing the flow of fuel to the fuel nozzle.

More specifically, for the embodiment shown, providing the flow of fuel to the fuel nozzle during the second condition at (**320**) includes at (**322**) providing a second flow of fuel to the fuel nozzle of the aeronautical gas turbine engine. An oxygen content of the volume of fuel in the fuel nozzle after ceasing providing the flow of fuel to the fuel nozzle at (**310**) is a first value, and the oxygen content of the second flow of fuel provided to the fuel nozzle during the second condition at (**322**) is a second value. The second value is equal to at least 1.5 times the first value. More specifically, in at least certain exemplary aspects the second value is equal to at least three times the first value, such as at least five times the first value, such as up to 100 times the first value.

In certain exemplary aspects, the second condition is a flight condition of the engine. For example, in certain exemplary aspects, the second condition is a takeoff flight condition, a climb flight condition, or both.

Referring still to the exemplary aspect of FIG. **8**, the method further includes at (**324**) providing a flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during a third condition separate from the wind down condition and the second condition. Providing the flow of fuel to the fuel nozzle during the third condition at (**324**) includes at (**326**) providing a third flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during the third. Similar to the exemplary aspects above, the oxygen content of the third flow of fuel provided to the fuel nozzle during the third condition is a third value. The third value is less than the second value and greater than the first value. With such an exemplary aspect, it will be appreciated that the second condition is a relatively high power flight condition, and the third condition is a relatively low power flight condition. For example, the second condition may be a takeoff flight condition, a climb flight condition, or both, and the third condition may be a cruise flight condition.

In certain exemplary aspects, a primary fuel oxygen reduction unit may be operated during the second and third conditions (and optionally during the first condition) (see FIG. **1**).

In such a manner, it will be appreciated that a fuel flow to the fuel nozzles is higher during the second and third conditions, than during the wind down condition. In such a manner the fuel is not exposed to the high temperatures for as long, and the volume of fuel thorough the fuel nozzle is greater, such that there is less risk of fuel coking within the nozzle.

Further aspects of the invention are provided by the subject matter of the following clauses:

A method of operating a fuel system for an aeronautical gas turbine engine, the method comprising: providing a flow of fuel to a fuel nozzle of the aeronautical gas turbine engine during a wind down condition; operating a fuel oxygen reduction unit to reduce an oxygen content of the flow of fuel provided to the fuel nozzle of the aeronautical gas turbine engine during the wind down condition; and ceasing providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine, the fuel nozzle comprising a volume of fuel after ceasing providing the flow of fuel to the fuel nozzle; wherein operating the fuel oxygen reduction unit comprises operating the fuel oxygen reduction unit to reduce an oxygen content of the volume of fuel in the fuel nozzle to less than 20 parts per million.

The method of one or more of these clauses, wherein operating the fuel oxygen reduction unit comprises operating the fuel oxygen reduction unit to reduce the oxygen content of the volume of fuel in the fuel nozzle to less than 15 parts per million.

The method of one or more of these clauses, further comprising: operating the aeronautical gas turbine engine during an idle condition, wherein the gas turbine engine defines a turbine inlet temperature greater than 1000 degrees Fahrenheit while the aeronautical gas turbine engine is operating during the idle condition.

The method of one or more of these clauses, wherein operating the fuel oxygen reduction unit comprises operating the fuel oxygen reduction unit substantially exclusively during the wind down condition.

The method of one or more of these clauses, wherein the fuel oxygen reduction unit defines a maximum operating time of one hour or less per flight mission.

The method of one or more of these clauses, wherein the aeronautical gas turbine engine is incorporated into an aircraft, wherein the aircraft defines a maximum fuel capacity, wherein the fuel oxygen reduction unit defines a maximum volume of fuel throughput per flight mission, and wherein the maximum volume of fuel throughput is less than 10 percent of the maximum fuel capacity of the aircraft.

The method of one or more of these clauses, further comprising: operating the aeronautical gas turbine engine during a cruise condition, wherein operating the aeronautical gas turbine engine during the cruise condition comprises providing a fuel flow to a combustion section of the aeronautical gas turbine engine at a cruise condition flowrate, wherein the fuel oxygen reduction unit defines a maximum fuel flowrate capacity, and wherein the maximum fuel flowrate capacity of the fuel oxygen reduction unit is less than the cruise condition flowrate.

The method of one or more of these clauses, further comprising: providing a flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during a second condition separate from the wind down condition, wherein an oxygen content of the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during the second condition is greater than the oxygen content of the volume of fuel in the fuel nozzle after ceasing providing the flow of fuel to the fuel nozzle.

The method of one or more of these clauses, wherein the oxygen content of the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during the flight condition is at least 1.5 times greater than the oxygen content of the volume of fuel in the fuel nozzle after ceasing providing the flow of fuel to the fuel nozzle.

The method of one or more of these clauses, further comprising: providing a second flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during a second condition separate from the wind down condition, wherein an oxygen content of the volume of fuel in the fuel nozzle after ceasing providing the flow of fuel to the fuel nozzle is a first value, wherein the oxygen content of the second flow of fuel provided to the fuel nozzle during the second condition is a second value, and wherein the second value is equal to at least 1.5 times the first value.

The method of one or more of these clauses, wherein the second value is equal to at least 3 times the first value.

The method of one or more of these clauses, wherein the second condition is a flight condition.

The method of one or more of these clauses, wherein the second condition is a takeoff flight condition, a climb flight condition, or both.

The method of one or more of these clauses, further comprising: providing a third flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during a third condition separate from the wind down condition, wherein the oxygen content of the third flow of fuel provided to the fuel nozzle during the third condition is a third value, wherein the third value is less than the first value, wherein the second condition is a relatively high power flight condition, and wherein the third condition is a relatively low power flight condition.

The method of one or more of these clauses, wherein the volume of fuel in the fuel nozzle is at least 10 milliliters of fuel.

The method of one or more of these clauses, wherein ceasing providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine comprises maintaining the volume of fuel in the fuel nozzle during and after the wind down condition.

An aircraft system comprising: an aeronautical gas turbine engine having a combustion section with a fuel nozzle; and a fuel system comprising a fuel source, a fuel delivery assembly, and a fuel oxygen reduction unit, wherein the fuel delivery assembly is configured to provide a flow of fuel to the fuel nozzle, and wherein the fuel oxygen reduction unit is in communication with the fuel source, the fuel delivery assembly, or both; and a controller operable with the gas turbine engine, the fuel system, or both configured to provide a flow of fuel from the fuel system to the fuel nozzle of the aeronautical gas turbine engine during a wind down condition; operate the fuel oxygen reduction unit to reduce an oxygen content of the flow of fuel provided to the fuel nozzle of the aeronautical gas turbine engine during the wind down condition; and cease providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine, the fuel nozzle comprising a volume of fuel after ceasing providing the flow of fuel to the fuel nozzle; wherein in operating the fuel oxygen reduction unit the controller is configured to operate the fuel oxygen reduction unit to reduce an oxygen content of the volume of fuel in the fuel nozzle to less than 20 parts per million.

The aircraft system of one or more of these clauses, wherein operating the fuel oxygen reduction unit comprises operating the fuel oxygen reduction unit to reduce the oxygen content of the volume of fuel in the fuel nozzle to less than 15 parts per million.

What is claimed is:

1. A method of operating a fuel system for an aeronautical gas turbine engine, the method comprising:

operating the aeronautical gas turbine engine during a cruise condition, wherein operating the aeronautical gas turbine engine during the cruise condition comprises providing a fuel flow to a combustion section of the aeronautical gas turbine engine at a cruise condition flowrate;

providing a flow of fuel to a fuel nozzle of the aeronautical gas turbine engine during a wind down condition;

operating a fuel oxygen reduction unit to reduce an oxygen content of the flow of fuel provided to the fuel nozzle of the aeronautical gas turbine engine during the wind down condition; and

ceasing providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine, the fuel nozzle comprising a volume of fuel after ceasing providing the flow of fuel to the fuel nozzle;

wherein operating the fuel oxygen reduction unit comprises operating the fuel oxygen reduction unit to reduce an oxygen content of the volume of fuel in the fuel nozzle to less than 20 parts per million;

wherein the fuel oxygen reduction unit defines a maximum fuel flowrate capacity of the fuel oxygen reduction unit, and wherein the maximum fuel flowrate capacity of the fuel oxygen reduction unit is less than the cruise condition flowrate.

2. The method of claim **1**, wherein operating the fuel oxygen reduction unit comprises operating the fuel oxygen reduction unit to reduce the oxygen content of the volume of fuel in the fuel nozzle to less than 15 parts per million.

3. The method of claim **1**, further comprising:

operating the aeronautical gas turbine engine during an idle condition, wherein the gas turbine engine defines a turbine inlet temperature greater than 1000 degrees Fahrenheit while the aeronautical gas turbine engine is operating during the idle condition.

4. The method of claim **1**, wherein the volume of fuel in the fuel nozzle is at least 10 milliliters of fuel.

5. The method of claim **1**, wherein operating the fuel oxygen reduction unit comprises operating the fuel oxygen reduction unit substantially exclusively during the wind down condition.

6. The method of claim **1**, wherein the fuel oxygen reduction unit defines a maximum operating time of one hour or less per flight mission.

7. The method of claim **1**, wherein the aeronautical gas turbine engine is incorporated into an aircraft, wherein the aircraft defines a maximum fuel capacity, wherein the fuel oxygen reduction unit defines a maximum volume of fuel throughput per flight mission, and wherein the maximum volume of fuel throughput is less than 10 percent of the maximum fuel capacity of the aircraft, wherein the maximum volume of fuel throughput per flight mission of the fuel oxygen reduction unit is a maximum amount of fuel the fuel oxygen reduction unit treats at a level within about 50 percent of its maximum efficiency.

8. The method of claim **1**, further comprising:

providing a flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during a second condition separate from the wind down condition, wherein an oxygen content of the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during the second condition is greater than the oxygen content of the volume of fuel in the fuel nozzle after ceasing providing the flow of fuel to the fuel nozzle.

9. The method of claim **8**, wherein the oxygen content of the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during the second condition is at least 1.5

times greater than the oxygen content of the volume of fuel in the fuel nozzle after ceasing providing the flow of fuel to the fuel nozzle.

10. The method of claim **1**, further comprising:

providing a second flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during a second condition separate from the wind down condition, wherein an oxygen content of the volume of fuel in the fuel nozzle after ceasing providing the flow of fuel to the fuel nozzle is a first value, wherein the oxygen content of the second flow of fuel provided to the fuel nozzle during the second condition is a second value, and wherein the second value is equal to at least 1.5 times the first value.

11. The method of claim **10**, wherein the second value is equal to at least 3 times the first value.

12. The method of claim **10**, wherein the second condition is a flight condition.

13. The method of claim **10**, wherein the second condition is a takeoff flight condition, a climb flight condition, or both.

14. The method of claim **10**, further comprising:

providing a third flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during a third condition separate from the wind down condition, wherein the oxygen content of the third flow of fuel provided to the fuel nozzle during the third condition is a third value, wherein the third value is less than the first value, wherein the second condition is a relatively high power flight condition, and wherein the third condition is a relatively low power flight condition.

15. The method of claim **1**, wherein ceasing providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine comprises maintaining the volume of fuel in the fuel nozzle during and after the wind down condition.

16. An aircraft system comprising:

an aeronautical gas turbine engine having a combustion section with a fuel nozzle; and

a fuel system comprising a fuel source, a fuel delivery assembly, and a fuel oxygen reduction unit, wherein the fuel delivery assembly is configured to provide a flow of fuel to the fuel nozzle, and wherein the fuel oxygen reduction unit is in communication with the fuel source, the fuel delivery assembly, or both; and

a controller operable with the gas turbine engine, the fuel system, or both, wherein the controller is configured to:

provide a flow of fuel from the fuel system to the fuel nozzle of the aeronautical gas turbine engine during a wind down condition;

provide a flow of fuel from the fuel system to a combustion section of the aeronautical gas turbine engine at a cruise condition flowrate during a cruise condition;

operate the fuel oxygen reduction unit to reduce an oxygen content of the flow of fuel provided to the fuel nozzle of the aeronautical gas turbine engine during the wind down condition; and

cease providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine, the fuel nozzle comprising a volume of fuel after ceasing providing the flow of fuel to the fuel nozzle;

wherein in operating the fuel oxygen reduction unit the controller is configured to operate the fuel oxygen reduction unit to reduce an oxygen content of the volume of fuel in the fuel nozzle to less than 20 parts per million;

wherein the fuel oxygen reduction unit defines a maximum fuel flowrate capacity of the fuel oxygen reduction unit, and wherein the maximum fuel flowrate capacity of the fuel oxygen reduction unit is less than the cruise condition flowrate.

17. The aircraft system of claim **16**, wherein operating the fuel oxygen reduction unit comprises operating the fuel oxygen reduction unit to reduce the oxygen content of the volume of fuel in the fuel nozzle to less than 15 parts per million.

18. The aircraft system of claim **16**, wherein the volume of fuel in the fuel nozzle is at least 10 milliliters of fuel.

19. A method of operating a fuel system for an aeronautical gas turbine engine, the method comprising:

providing a flow of fuel to a fuel nozzle of the aeronautical gas turbine engine during a wind down condition;

operating a fuel oxygen reduction unit to reduce an oxygen content of the flow of fuel provided to the fuel nozzle of the aeronautical gas turbine engine during the wind down condition; and

ceasing providing the flow of fuel to the fuel nozzle of the aeronautical gas turbine engine, the fuel nozzle comprising a volume of fuel after ceasing providing the flow of fuel to the fuel nozzle;

providing a second flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during a second condition separate from the wind down condition, wherein the second condition is a relatively high power flight condition, wherein an oxygen content of the volume of fuel in the fuel nozzle after ceasing providing the flow of fuel to the fuel nozzle is a first value, wherein the oxygen content of the second flow of fuel provided to the fuel nozzle during the second condition is a second value, and wherein the second value is equal to at least 1.5 times the first value; and

providing a third flow of fuel to the fuel nozzle of the aeronautical gas turbine engine during a third condition separate from the wind down condition, wherein the third condition is a relatively low power flight condition, wherein the oxygen content of the third flow of fuel provided to the fuel nozzle during the third condition is a third value, wherein the third value is less than the first value;

wherein operating the fuel oxygen reduction unit comprises operating the fuel oxygen reduction unit to reduce an oxygen content of the volume of fuel in the fuel nozzle to less than 20 parts per million.

20. The method of claim **19**, wherein operating the fuel oxygen reduction unit comprises operating the fuel oxygen reduction unit substantially exclusively during the wind down condition.

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